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Statistical study of the ULF Pc4–Pc5 range fluctuations in the vicinity of Earth's magnetopause and correlation with the Low Latitude Boundary Layer thickness

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Abstract

The main generation mechanisms for the Earth's Low Latitude Boundary Layer (LLBL) are considered to be magnetic reconnection, viscous interactions such as Kelvin–Helmholtz instability and associated plasma mixing and diffusion. We have performed a statistical study of the Ultra Low Frequency (ULF) fluctuation power at the Pc4–Pc5 range using ≈6 years of THEMIS measurements of the plasma velocity and magnetic field. The results reveal a clear dawn–dusk asymmetry showing that the fluctuation power is typically more enhanced in the vicinity of the magnetopause downstream of the quasi-parallel shock. The statistical study of the V_x-component of the plasma velocity indicates that the LLBL is also thicker on the dawn-sector. These results may suggest that the physical mechanisms that provide power in the Pc4–Pc5 range are more effective on the dawn-sector and provide a means for a more effective LLBL generation.

Keywords: Magnetosheath; Magnetosphere; Velocity and magnetic field turbulence; Kelvin–Helmholtz instability

1. Introduction

Earth's magnetic field forms a cavity to the solar wind called the magnetosphere. The magnetopause (Chapman and Ferraro, 1931) is a current layer with a finite thickness shielding, albeit not perfectly, the solar wind plasma from the magnetospheric plasma. In the solar wind frame, it looks as if supersonic magnetosphere is approaching it, which forms a standing shock wave, the bow shock, in front of the magnetosphere. The bow shock slows down, compresses and heats the solar wind plasma forming a turbulent boundary layer called the magnetosheath between the magnetopause and the shock. The plasma and magnetic field properties of the magnetosheath determine the efficiency of the physical mechanisms that operate at the magnetopause. These processes are ultimately responsible for coupling the Solar Wind into the Earth's Magnetosphere. The main physical mechanisms that produce energy, momentum and mass transport at the magnetopause are magnetic reconnection (Dungey, 1961; Song and Russell, 1992; Russell et al., 2000), Viscous interaction and Kelvin–Helmholtz instability (KHI) (Axford and Hines, 1961; Miura, 1984; Fujimoto and Terasawa, 1994; Fujimoto and Terasawa, 1995; Thomas and Winske, 1993; Fairfield et al., 2000; Otto and Fairfield, 2000; Nykyri and Otto, 2001; Nakamura and Fujimoto, 2005; Nykyri et al., 2006; Nakamura et al., 2006; Hasegawa et al., 2009), and Kinetic Alfvén Waves (KAW) (Johnson et al., 1997, 2001).

During recent years, multi-spacecraft missions such as Cluster (Escoubet et al., 2001) and THEMIS (Time History

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of Events and Macroscale Interactions during Substorms) (Angelopoulos, 2008) have made possible significant advances in understanding the formation, structure, fluctuation and wave mode properties of the boundaries surrounding the Earth's magnetosphere both at the high-latitudes close to cusps (Lavraud et al., 2002; Nykyri et al., 2003; Němeček et al., 2003; Nykyri et al., 2004; Grison et al., 2005; Lavraud et al., 2004; Lavraud et al., 2005; Sundkvist et al., 2005; Nykyri et al., 2006; Walsh et al., 2007; Nykyri et al., 2011a,b; Nykyri et al., 2012) and at the low latitudes (Lucek et al., 2001; Longmore et al., 2005; Walsh et al., 2012; Gutynska et al., 2012; Samsonov et al., 2012; Šafránková et al., 2012; Savin et al., 2012; Dimmock and Nykyri, 2013; Lavraud et al., 2013; Dimmock et al., 2014; Karimabadi et al., 2014; Dimmock et al., 2015). At low latitudes this boundary layer is called the Low Latitude Boundary Layer (LLBL) and a great historical review on pioneering observations and theory on the formation of the boundary layers and the LLBL be read in the article by Eastman (2003). A clear example of the solar wind influence on the magnetosphere is that the magnetospheric plasma sheet temperature and density are correlated with the solar wind properties on a time scale of 1–2 h (Borovsky et al., 1998). The plasma sheet is the magnetospheric continuation of the LLBL and is mostly on closed field lines and contains the cross-tail current. For southward IMF the plasma sheet is typically hot and tenuous, which is attributed to the substorm physics whereas the northward IMF conditions have been associated with the presence of the cold, dense plasma sheet (Fairfield et al., 1981; Lennartsson, 1992).

There also exists a dawn–dusk temperature asymmetry in the flanks of the plasma sheet - the cold component ions are hotter by 30–40% at the dawnside plasma sheet compared to the duskside plasma sheet (Wing et al., 2005). Our recent statistical study of magnetosheath temperatures using 6+ years of THEMIS data indicates that ion magnetosheath temperatures downstream of quasi-parallel (dawn-flank for Parker-Spiral IMF) bow shock are only 10–15% higher than downstream of the quasi-perpendicular shock (Dimmock et al., 2015). This magnetosheath temperature asymmetry is therefore likely inadequate to cause the observed level of the plasma sheet temperature asymmetry. This suggest that additional physical mechanisms at the dawn-flank are responsible for this heating.

Modeling of the magnetosheath properties as a function of upstream solar wind conditions has shown, that the dawn-sector flank is statistically more unstable to KHI than dusk flank during Parker Spiral IMF, because tangential magnetic field along magnetopause is smaller at the dawn-side compared to the dusk-side (Nykyri, 2013). The KHI and associated reconnection, diffusion and kinetic Alfvén wave activity are considered as one of the candidate mechanisms for LLBL and cold dense plasma sheet generation, in particular for increasing tailward distances. A recent statistical study by Kavosi and Raeder (2015) indicates that KH waves occur very frequently (19% of the time from 7 years of THEMIS magnetopause crossings) and for various IMF orientations and solar wind conditions. The KH occurrence rate was observed to increase with solar wind speed, Alfvén Mach number and number density. Also, a polar orbiting DE-1 satellite found a clear dawn favoured asymmetry in transverse Pc5 pulsations (Nosé et al., 1995). They found that the higher the solar wind velocity, the more frequent the Pc5 occurrence. They suggested that the energy source of these Pc5 range fluctuations were produced by KHI. Indeed, the fastest growing KHI has an angular frequency of $f \approx V_{shear}/2\Delta$, where Δ is the boundary layer thickness and V_{shear}, is the magnitude of the velocity shear, coinciding with the Pc3-Pc5 range geomagnetic fluctuations (Miura and Pritchett, 1982).

An important aspect of the KHI is it's convective nature and its ability to produce a thick boundary layer as it propagates from the source region along the tail via diffusive processes and reconnection (Fujimoto and Terasawa, 1994; Nykyri and Otto, 2001; Nykyri and Otto, 2004; Nykyri et al., 2006; Hasegawa et al., 2009; Cowee et al., 2010). A more complete description of various processes, including double high-latitude reconnection (Li et al., 2005) and impulsive penetration (Lemaire, 1977; Echim and Lemaire, 2000), that play role in LLBL generation can be read in recent review by Wing et al. (2014). Fig. 1 shows a snapshot of the 2.5 D KHI simulation during strongly northward IMF (magnetic field is at 5° angle from perpendicular direction with respect to shear flow plane). Fig. 2 shows a virtual probe measurements in the simulation domain. Even for initially strongly parallel fields across the velocity shear layer, the KHI can generate anti-parallel magnetic fields (M and N-components) in shear flow plane which leads to strong filamentary current layers where reconnection can occur (Nykyri and Otto, 2001). This can lead to effective plasma mixing and LLBL generation. Fig. 2 indicates that virtual spacecraft (sitting in the centre of the simulation box) measures 1–3 min variations in plasma, velocity and magnetic field parameters when it encounters KH waves. Between 00:01 h and 00:07 h the variations in B_T, B_L, N and T are more regular and show $\approx$2 min periodicity. After 00:07 h, the reconnection process has produced very filamentary structures on magnetospheric side of the initial shear flow boundary (see right panel of Fig. 1), which generates more high frequency variations in velocity and magnetic field observed by the virtual probe. Note that initially there was no normal component (N) and the magnetic fields were parallel at the both sides of the boundary along the tailward (M-component) direction. The KHI dynamics creates a non-zero B_N and anti-parallel B_M and B_N components leading to formation of strong current layers. The period depends on the wave length, which in turn depends on the velocity shear layer thickness at the source region of the instability. Depending on the initial magnetic field polarity, the strength of the asymmetry across the velocity shear layer and how the virtual probe crosses the wave, different